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**The All Seeing Eye: Space-Based Persistent Surveillance in 2030**

by

Jason C. Eisenreich, Major, United States Air Force

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Advisor: Lieutenant Colonel Angela G. Stout

Maxwell Air Force Base, Alabama

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## **Preface**

I wrote this paper as part of the Blue Horizons research elective at the Air Command and Staff College. Blue Horizons looks to identify potential capabilities for the U.S. Air Force in the year 2030. To me, as a space professional, the implication of threats to our space systems are very scary. While our space systems do not reside on the front lines of any conflict at this time, the proliferation of anti-space weapons ranging from communications jamming to kinetic threats present the very real possibility that the tremendous capabilities of our space systems can be threatened. These capabilities do have a direct impact on front lines forces that have become accustomed to their availability.

The most publicized example of the potential threats is the Chinese direct ascent anti-satellite test in January 2007. In looking to the 2030 timeframe, systems such as these will only become more capable as well as more widespread. These weapons can hold assets in low earth orbit, including vital government and commercial remote sensing assets, in jeopardy. For this paper I focused on today's commercial imaging capabilities which have become a very important asset to today's military. These systems operate in low earth orbit and will become increasingly vulnerable as anti-satellite weapons proliferate.

I wrote this paper to an audience with a background in space but not necessarily space expertise. I have included an appendix with some definitions of a few of the terms which are not necessarily obvious to the casual observer.

I would like to thank my advisor, Lieutenant Colonel Angela Stout, for her guidance in getting me through this project. Her insights have helped focused what turned out to be a broader topic than I originally imagined. I would also like to thank Colonel Scott Larrimore at the Space and Missile Systems Center and Major Luke Gargas at the Air Force Research

Laboratory (AFRL) for putting me in contact with technical experts in technology areas with which I was not very familiar. Some of these experts I would like to thank are Dr Greg Spanjers and Mr. Tom Roberts at AFRL for the education they gave me on large focal planes as well as Dr Seth Lacy and Dr Steven Lane also at AFRL for their help in understanding the deployable optics concepts they have investigated. Without the support of these people, I would not have been able to complete this project.

Finally, I would like to give thanks my wife, Kody, and boys, Bryce and Logan, for the support they have given me throughout this school year and my entire career. They are my motivation for everything I do.



## **Abstract**

This research paper investigates the space environment in the 2030 timeframe with respect to the important space-based earth surveillance mission. It attempts to answer the question: “Can the U.S. field a persistent space-based surveillance capability in an operational domain that is increasingly challenged by adversary threats?” To answer this question, the paper looks at the nature of existing threats and the likely capability developments in the next 20 years. To counter the threats, the paper investigates a geosynchronous orbit based surveillance system. Such a system would be beyond the reach of current anti-satellite weapons. However, significant technical hurdles remain to make such a system a reality.

Operating in geosynchronous orbit affords a system the ability to remain positioned over one spot on the planet resulting in a persistent capability. However, the increased distance from earth requires optics on a scale that first, stretches the limits of available launch vehicles, and second, tests the manufacturing capability of our nation. This paper looks at advances in deployable optics and expansion in focal plane size to determine if when combined, the two components can meet the system’s requirements. Finally, the capabilities of the new system are crosschecked against the expected advances in space threats to determine if a geosynchronous system can accomplish its mission without being contested.

## **Introduction**

Since the launch of Explorer 1 in 1958, the U.S. has increasingly exploited the benefits of space-based systems.<sup>1</sup> This exploitation has created a dependence of the “security and economic well being” of the U.S. and her allies on the ability to operate space systems.<sup>2</sup> This dependence on space systems runs from use of the Global Positioning System’s timing signal for banking transactions to weather prediction products from the National Oceanographic and Atmospheric Administration’s (NOAA) geostationary and polar-orbiting satellites.

The reliance on space systems is especially true for operations of the U.S. armed forces. In testimony before the Strategic Forces Subcommittee of the House Armed Services Committee, General Kevin P. Chilton, Commander, U.S. Strategic Command, stated that space capabilities “are integrated into nearly all facets of US military operations and give the American and coalition warfighter an unparalleled advantage.”<sup>3</sup> These capabilities include communications, navigation and positioning, missile warning, intelligence, surveillance, and reconnaissance (ISR), and environmental monitoring. Until recently, the United States’ access to space has been constrained only by internal launch vehicle and satellite production and operations limitations.

On 11 January 2007, China used a direct ascent anti-satellite (ASAT) weapon to destroy one of their obsolete weather satellites in low earth orbit (LEO) [See Figure 1].<sup>4</sup> Coupled with Chinese activity to actively blind a U.S. reconnaissance satellite using a ground based laser in 2006, unfettered U.S. access to space is no longer a sure thing, especially in times of conflict.<sup>5</sup> China and other nations are aware of both U.S. dominance in the space arena and U.S. dependence on space capabilities. This results in an attractive target for a nation with potentially weaker conventional forces to have a disproportionate effect on U.S. capabilities. To ensure that

American warfighters maintain their unparalleled advantage, the nation must look forward to an expansion of threats to space systems and develop counter-measures that protect this vital capability.

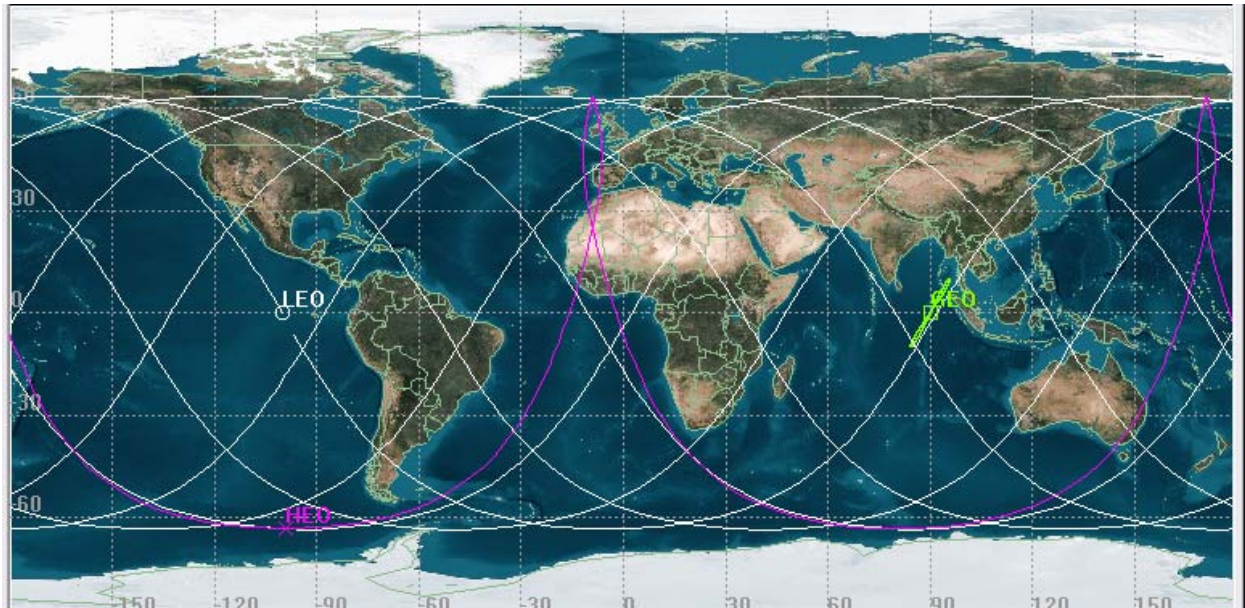
One space capability particularly vulnerable to the two threats mentioned is earth observation, provided by both government and commercial assets. These satellites are critical to fulfilling the combatant commander's need for ISR-related information. These satellites are essentially telescopes in space peering at the Earth's surface. The physics of optics, orbital mechanics, and current technology, both in optics and launch systems, have deemed near-polar, LEO orbits as the only feasible option for comprehensive coverage at the required resolution. These orbits are typically sun-synchronous to afford a constant orientation with respect to the sun at an altitude of about 500 km to attain a high level of resolution while minimizing atmospheric drag.<sup>6</sup>

While the LEO orbits enable high resolution imaging, they are very vulnerable to both threats mentioned above, direct ascent ASATs and ground-based lasers. In addition to this vulnerability, current reconnaissance systems have a significant limitation which directly impacts their ability to provide necessary information to national decision makers and combatant forces. This is their limited time over a specific target. Their ability to slew from a nadir-pointing orientation works to increase the time a target is in view and decrease the time between views. However, their operational altitude restricts their capacity for persistent observation. To combat this in current theaters of operation, the U.S. military has turned to airborne assets, in particular unmanned aerial vehicles. This represents a sufficient solution for current operations due to unrestrained overflight of the areas of interest. This does not, however, address the need for persistent coverage of denied areas.

In order to lessen the threat of direct ascent ASAT and ground based lasers and increase persistent capabilities, the nation must investigate alternative means of accomplishing the mission of providing overhead surveillance. One potential solution is to field an optical system in a geostationary orbit (GEO) [See Figure 1]. A GEO-based system would have many benefits. First, the range of current anti-satellite weapons is limited to LEO. Second, an object in a geostationary orbit remains over the same point on the Earth, thereby keeping any point on the Earth beneath that orbit in its field of view, eliminating revisit times. The concepts of placing an Earth observing satellite in GEO have been proven by both the Defense Satellite Program (DSP) missile warning satellites and NOAA's Geostationary Operational Environmental Satellites (GOES) which provide long-term weather forecasting.

With these benefits come some significant obstacles that will need to be overcome to make a GEO-based optical system a reality. Currently, the Hubble Space Telescope is the largest aperture optical system on orbit, with a 2.4m primary mirror.<sup>7</sup> In order to match the 0.5m resolution of today's best commercial system, a GEO-based system would require an 8m or larger mirror.<sup>8</sup> As current launch vehicles are not equipped to handle a mirror of that size, a deployable mirror is needed. Such a mirror will require advances in structural elements and control systems to ensure proper alignment throughout the systems lifetime. The large field of view of a GEO-based system also requires significant progress in focal plane technology. Fielding an equivalent capability to today's systems will necessitate development of staring focal planes. Today's optical systems typically use a push-broom focal plane which is a set of detectors arranged linearly across the ground track.<sup>9</sup> The detectors capture a line of images as the satellite moves over the ground to build up an image. The lack of relative motion with the

ground makes a staring sensor a more appealing option. Such sensors are comprised of a matrix of detectors that simultaneously image an area to produce a picture.



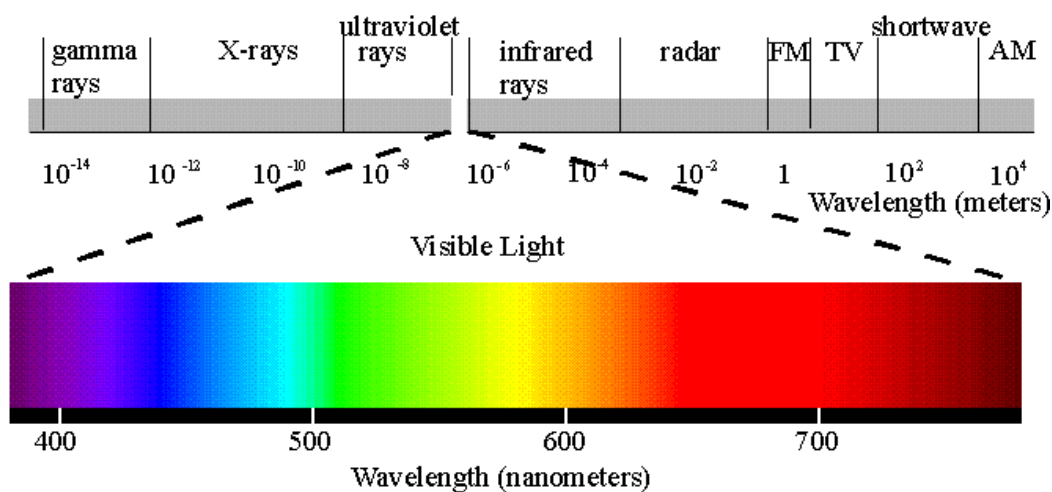
**Figure 1 – 24 Hour Period LEO / HEO / GEO Orbits**

## **Thesis**

While developing an operational persistent surveillance system for use in GEO is possible by 2030, space threats will also mature to the point that there will be no truly “safe” operating area in space. To gain the tremendous benefits that a GEO-based surveillance system would afford, the U.S. first must develop a comprehensive space situational awareness capability that allows the tracking and identification of the smallest microsattellites in all orbital regimes and pair that with a space asset protection capability that can defend our nation’s most vital systems against adversary threats and attacks.

### **Current Space-Based Earth Surveillance Systems**

Currently Space-based Earth surveillance systems come in many different forms to include low resolution multi-color imagers such as LANDSAT, missile warning sensors observing in the infrared spectrum, and high resolution visible sensors which are the focus of this research.<sup>10</sup> In the United States, such sensors come in two varieties, classified satellites procured and operated by the National Reconnaissance Office (NRO) and commercial satellites built and operated by corporations. These sensors use the visible portion of the electromagnetic spectrum (Figure 2) to produce images for uses ranging from military intelligence to mapping and



**Figure 2 – Electromagnetic Spectrum**

environmental monitoring. Due to the classified nature of NRO satellites, this paper will use current commercial satellites as the point of departure.

There are two primary corporations in the commercial satellite imagery market today, GeoEye, based in Dulles, Virginia, and DigitalGlobe, based in Longmont, Colorado. Both

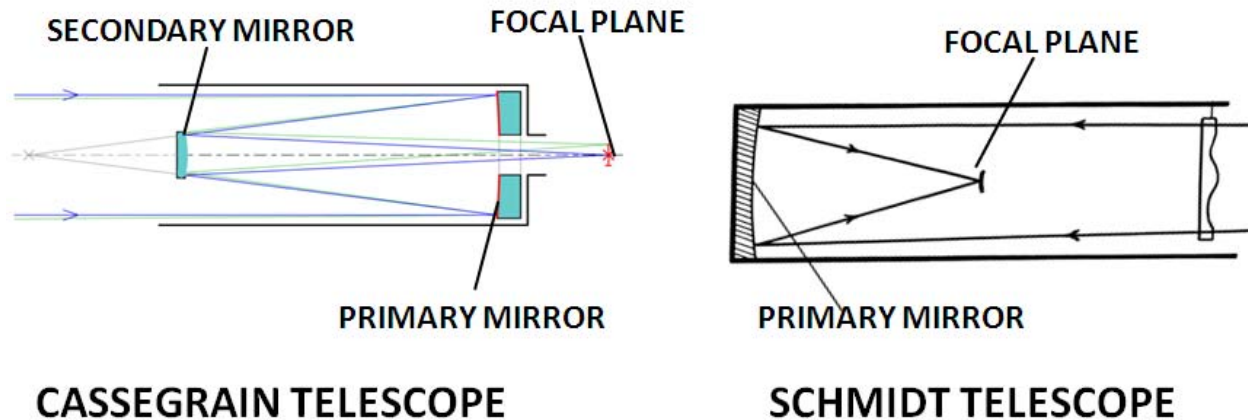
companies have developed and deployed a number of imaging spacecraft into LEO offering both panchromatic and multispectral images to customers around the world. DigitalGlobe's most capable satellite is WorldView-1 launched in September 2007 while GeoEye's best offering is GeoEye-1 launched a year later.<sup>11</sup> Figure 3 shows specifications of these two spacecraft. While both satellites perform similar missions, the table shows that they each have design characteristics which enable different mission characteristics. For example, while WorldView-1 operates at a lower altitude, GeoEye-1's sensor design provides higher resolution. On the other hand, WorldView-1's sensor design allows pictures to be taken over a larger swath width. Another characteristic impacted by the altitude is the revisit rate. Because GeoEye-1 is stationed at a higher altitude, it is able to provide more frequent revisit opportunities.

|                              | <b>WorldView-1</b>  | <b>GeoEye-1</b>               |
|------------------------------|---|-------------------------------|
| <b>Launch Date</b>           | 18 Sep 07   | 6 Sep 08                      |
| <b>Orbital Altitude</b>      | 496 km  | 681 km                        |
| <b>Spatial Resolution</b>    | 50 cm Ground Sample Distance (GSD) at nadir<br>59 cm GSD at 25° off nadir | 41 cm GSD at nadir            |
| <b>Sensor Bands</b>          | Panchromatic  | Panchromatic<br>Multispectral |
| <b>Swath Width</b>           | 17.6 km at nadir  | 15.2 km at nadir              |
| <b>Maximum Viewing Angle</b> | +/- 45° (1,036 km swath width)  | +/- 60°                       |
| <b>Revisit Frequency</b>     | 4.6 days at 25° nadir or less   | Less than 3 days              |

**Figure 3 - WorldView-1 and GeoEye-1 Specifications<sup>12</sup>**

Optical earth observation satellites are essentially telescopes in the space. While the entire system is very complicated, the most important portions of the optical train are fairly simple. The two essential elements are the aperture and the sensor. The aperture is a reflecting surface that focuses the incoming light onto the focal plane where the sensor is located. Figure 4 shows two common optical trains, a Schmidt telescope and a Cassegrain telescope. The Cassegrain is often preferred for space use because it allows for the longest possible focal length, increasing the magnification.<sup>13</sup> However, the extra reflecting surface does add complexity. In

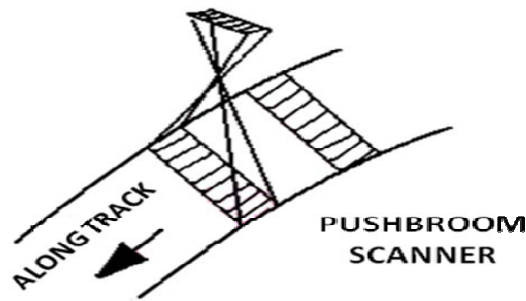
most optical systems, charged couple devices (CCD) are used to capture the images reflected onto the focal plane.<sup>14</sup> The CCDs capture the photons reflected of the mirrors and digitize the information for processing and transmittal to a ground station.



**Figure 4 - Cassegrain and Schmidt Telescopes<sup>15</sup>**

Both example satellites are push broom scanning sensors with slewing capabilities. A push broom sensor has detectors arranged linearly across the satellite's ground track. Each detector collects an image at intervals or integration times normally set to the time at which the sub-spacecraft point travels one ground pixel width.<sup>16</sup> As the spacecraft travels along the ground track, the collections of each integration time are assembled together into a single image. Figure 5 illustrates how a push broom scanner operates.<sup>17</sup> The slewing capability of the example spacecraft allows them to image off nadir as well as using the push broom detectors to take side by side images that when put together make a larger area image.





**Figure 5 - Push broom Scanner**

### **Capabilities and Limitations of Current Systems**

From these specifications, the capabilities and limitations of current systems are evident. By operating in LEO, today's imaging spacecraft are able to provide resolution high enough for almost any use, commercial or military. In fact, the U.S. government is so dependent on commercial imagery that it has entered into contracts with the corporations involved to ensure government input into satellite design characteristics and access to imagery products.<sup>18</sup> Both spacecraft in Figure 3 are in sun-synchronous orbits with orbital nodes of 10:30 a.m. This means that orbital mechanics cause their orbits to rotate at a rate that keeps them at an approximately constant orientation with the sun.<sup>19</sup> In the case of the example satellites, they pass over locations on the Earth at approximately 10:30 a.m. This is especially useful in determining change using images taken over multiple revisits.

The need to revisit targets is the largest weakness of today's earth-imaging systems. Because an object in LEO has an approximate orbital period of 90 minutes, the amount of time over a specific target is relatively small. The time over a target can be extended by equipping the spacecraft with the ability to slew, however, this increases the distance between the target and the satellite's sensors which will decrease the resolution. The revisit time can be shortened by deploying a constellation of satellites which are phased in their orbits to pass over targets on

different days. While this can shorten the time between revisit, it cannot eliminate gaps in coverage. Persistence has become a priority for senior leaders within the Department of Defense (DoD). In fact, Secretary of Defense Robert M. Gates touted the importance of persistent surveillance being provided by U.S. Air Force (USAF) Unmanned Aerial Vehicles (UAV) in the current conflicts in the U.S. Central Command (CENTCOM) area of operations as having saved countless lives.<sup>20</sup>

As Secretary Gates' statement implies, the focus of today's efforts to obtain persistent surveillance of the visual spectrum are focused on UAVs. Unmanned Aerial Vehicles offer an appealing option when overflight of the target is allowed such as in Iraq and Afghanistan today. Flying at lower altitudes allows for excellent resolution and long dwell times and multiple assets provide almost unlimited persistence. However, when the airspace around the target is denied, space becomes the preferred domain to use for obtaining the necessary imagery.

This hints at another important capability of current systems, their worldwide coverage. The nature of low earth orbits permits a satellite overflight of every location on Earth within a certain number of orbits depending on sensor design and orbital altitude. This worldwide visibility allows the satellites to be tasked to collect images of specified targets while flying overhead. For the military, this global capability for sensor tasking allows commanders the ability to receive relevant images around the world. While the ability to task provides important capabilities, the need to task is a limitation. The two example satellites have swath widths of less than 20 km. The swath width is the largest width of a nominal image. Both spacecraft have alternate modes that allow for larger area coverage. However, even the large area collections of these systems are limited to a 100 km width or less.<sup>21</sup> As a point of reference, GeoEye-1's largest contiguous large area collect is 300 km x 50 km (15,000 sq km).<sup>22</sup> Such an image would

represent only 3.4% of the area in Iraq.<sup>23</sup> To image the entire area of Iraq would take numerous passes overhead by one spacecraft or constellation of spacecraft. The relatively small fields of view of today's sensors seriously limit persistent capability.

In addition to the field of view, any optical system has a significant limitation in where it operates in the electromagnetic spectrum. Because these systems' sensors view in the visual portion of the spectrum, they are affected by darkness and clouds. Both of these natural phenomena prevent optical sensors from seeing to the ground. For this reason, any surveillance system must be an integrated system that includes assets that utilize the entire spectrum to ensure persistent surveillance of the earth.

Another limitation of current systems is their vulnerability to threats already in existence. Their location in LEO makes them susceptible to both direct ascent ASATs and ground based lasers that have been demonstrated by other nations. These satellites requirement for a low altitude to provide high resolution brings them well into range of these proven threats. The next section will go into the various threats to space systems both current and foreseen. In addition to the low altitude, the orbits of LEO satellites are very predictable aiding targeting of ASAT weapons. The predictability allows aids adversary denial and deception efforts. By knowing when and where the spacecraft are flying overhead, an adversary can hide activity in that location for the time that the satellite will be overhead.

### **Space Threat Background**

There are a number of threats to U.S. space systems. Most of the details about these threats are classified. Therefore, this section will provide generic explanation of a four different types of threats using open source information to provide some details about actual systems. The four types of systems covered are direct ascent ASATs, co-orbital ASATs, directed energy

weapons, and electromagnetic pulse weapons. A prerequisite for the first three weapons is the ability to track objects in space. Currently, the U.S. is the only country with a comprehensive worldwide ability to track objects in space. However, amateur satellite observers have developed an informal network that is able to very accurately characterize the orbits of almost all satellites.<sup>24</sup>

### **Direct Assent ASATs**

A direct assent ASAT is a ground based weapon consisting of a launch vehicle and a kill vehicle. The launch vehicles required for a direct assent vehicle are relatively simple. Any country with access to ballistic missile technology would be able to field the launch vehicle portion of a direct assent ASAT.<sup>25</sup> While the launch vehicle is relatively widespread technology, the kill vehicle is the critical component of the system. The kill vehicle contains terminal tracking and guidance, engagement, and fusing mechanisms.<sup>26</sup> The engagement mechanism can be a kinetic-only, explosive, or combination device. A kinetic-only warhead requires more precise guidance to ensure destruction of the target. Explosive weapons allow less precise guidance as the shrapnel spread by the detonation expands and increases the probability of hitting the target.

Both China and the United States have recently demonstrated direct assent ASAT weapons. In January 2007, China utilized a medium range missile to destroy a defunct Chinese weather satellite over 850 km above the earth.<sup>27</sup> This action demonstrated Chinese ability to engage any satellite operating in LEO. This episode also demonstrated the downside of using such weapons. The missile test broke the target satellite into over 35,000 pieces of space debris.<sup>28</sup> This debris cloud now presents a hazard to other satellites operating in the same area. While the details of the Chinese anti-satellite are either not known or classified, statements from

Chinese leaders imply that they see such weapons as a critical portion of their arsenal to counter U.S. reliance on and dominance in the space domain.

The United States demonstrated a direct ascent ASAT capability in February 2008. This was accomplished through modification of a Navy Standard Missile 3 (SM-3) to shoot down an incapacitated U.S. spy satellite which had a full tank of toxic hydrazine still aboard.<sup>29</sup> The effects of atmospheric drag were causing the deorbit of the satellite. Due to the risk of some hydrazine surviving reentry, the U.S. government chose to destroy the satellite and its hydrazine tank. While the primary mission of the ship-based SM-3 is ballistic missile defense, the requirements for intercepting a ballistic missile are similar to those necessary for destroying a satellite.

### **Co-Orbital ASATs**

A co-orbital ASAT is similar to a direct ascent ASAT except that the ASAT is launched into orbit and eventually rendezvous with its target. The ASAT could remain dormant in orbit indefinitely as long as it has fuel and power to be employed when called upon. The Soviet Union developed and operated a co-orbital ASAT beginning in 1971. Although never employed in hostility, it was last tested in 1982 and remained operational at least until 1991.<sup>30</sup> Weapons such as these are particularly threatening because of the fact that their threat does not dissipate some finite time after launch.

A co-orbital ASAT could accomplish its mission via a number of techniques. If it contains a kill vehicle, it could destroy the target. It could also conduct surveillance operations against a target or try to deny the adversary use of this asset by jamming communications or blocking the target's view of the earth and its ground station. While such actions would only

temporarily disable the target, it is less provocative and may not elicit as harsh of a reaction from the adversary.

There is also evidence of the ability to develop a co-orbital ASAT in the U.S. and Chinese space programs. China's Shenzhou-7 manned spacecraft was launched in September 2008 and had an accompanying satellite that was released the day after launch. This companion satellite proceeded to fly around the orbital vehicle, taking pictures and sending them to the ground for 100 days after the manned spacecraft returned to earth.<sup>31</sup> While this is a long way from an operational ASAT capability, it shows the required basic capability for rendezvous operations. Similarly, recent press reports indicate that the U.S. has employed covert inspection satellites to investigate a failed missile warning satellite.<sup>32</sup> Like the Chinese companion satellite, these inspection satellites are employing rendezvous operations that would be essential to a co-orbital ASAT either to destroy, disable, or observe an adversary satellite.

### **Directed Energy Weapons**

Directed energy weapons (DEW) come in two forms, high power microwave (HPM) and laser. Because of HPM range limitations, lasers have provided the most viable option as an ASAT weapon. Laser weapons could be used to either destroy a satellite or in the case of an optical satellite to either temporarily or permanently blind the sensor. Such weapons have been postulated and investigated for use on ground-based, air-based, and space-based platforms. Because the optical satellite is trying to gather images of the earth, a ground or sea-based laser would be able to target the satellite's sensor while a space-based laser would have to be positioned below, the spacecraft which would be very difficult for a LEO target. However, if the object is to destroy the target, a space-based laser has the benefit that its beam would not have to travel through the atmosphere, which dissipates the strength of the laser.

The U.S., China, and the Soviet Union have all demonstrated significant interest in lasers and their use as ASAT weapons. In the 1980s, the Soviets had at least three locations at which imagery showed signs of laser activity. These weapons are believed to have had lethal ranges of over 280 miles and the ability to damage at over 450 miles away.<sup>33</sup> With LEO ranging from 450 miles to 700 miles, the threat posed by these weapons and follow-on systems to satellites operating LEO, especially optical satellites, is very evident. Because an optical satellite functions by sensing the incoming light to compose an image, all a laser would have to do is saturate the sensor to impair its imaging ability. This is defined as dazzling.

According to former Director of the NRO, Donald Kerr, China has illuminated an U.S. reconnaissance satellite with a ground-based laser on at least one occasion.<sup>34</sup> This test corroborated previous Pentagon reports suggesting that China is developing ground-based lasers to target space-based reconnaissance systems.<sup>35</sup> China has also invested in laser technology for ballistic missile defense.<sup>36</sup> Because of the large amount of energy needed to destroy a ballistic missile and the sensitivity of a space-based optical system, such a system could be easily adapted for use against spacecraft.

In addition to the Soviet Union and China, the U.S. has conducted a great deal of laser research and development. The U.S. developed a ground-based midwave infrared chemical laser (MIRACL) for use in testing against U.S. satellites to determine vulnerabilities of these systems to lasers. This primary function was to aid in the development of defenses and countermeasures against adversary laser use. However, MIRACL is said to have also had a secondary mission as a weapons against adversary satellites.<sup>37</sup> Such dual capabilities make laser weapons extremely hard to define as a certain category of weapon.

### **Electromagnetic Pulse Weapons**

Upon detonation of a nuclear weapon, an electromagnetic pulse (EMP) propagates outward. The pulse can disrupt or destroy electronics in the vicinity. Such a detonation in space would have grave consequences for satellites operating in the area. As an example, in 1962 the U.S. conducted the “Starfish Prime” experiment in which a 1.4 megaton nuclear weapon was detonated at an altitude of 400 km. The resulting EMP caused permanent damage to the solar cells of three U.S. and British satellites in 1000 km orbits.<sup>38</sup> In addition, this test resulted in radiation being trapped in the Van Allen belts causing havoc with additional satellites.

While a very powerful weapon, an EMP weapon is also indiscriminate. Therefore, any nation utilizing such capability would also have to expect that its satellites will be destroyed or degraded as well. For a nation with a nascent or non-existent space capability, an EMP weapon presents a unique capability of inflicting an asymmetric impact on the U.S. Because U.S. dependence on satellite capabilities is so well known, any nation with a basic ballistic missile capability and access to a nuclear weapon could launch such an attack and destroy satellites already on orbit as well as make LEO an inoperable area for a significant amount of time. Not only large powers such as Russia and China have access to the components necessary for such an attack. Spacefaring nuclear nations like India could easily pair on hand capabilities to exercise this option. Also, smaller powers such as Pakistan, Iran, and North Korea would need only relatively small amounts of progress to be able to have such a capability.

### **Need for Persistent Surveillance**

In addition to the threats mentioned in the previous section, current space-based surveillance platforms are lacking in the amount of persistence they can provide to users. This lack of persistence limits the times at which satellites can provide access to specific targets. Adversary denial and deceptions efforts due to the predictability of the LEO orbits further limit



the utility of existing assets. Evidence for the need for persistence is seen in U.S. actions in Iraq and Afghanistan. To increase the overhead coverage in Iraq, the USAF has increased the number of around-the-clock UAV orbits from 12 to 27 within the last year.<sup>39</sup> This large number of continuous orbits is required due to the relatively small field of view of the UAV because of their operating altitude and onboard sensors.

This thirst for real-time awareness of events is not limited to the battlefield. The secrecy that shrouds the military capabilities of many potential adversaries drives a similar need for persistent real-time coverage of areas such as China, Iran, North Korea, and Russia which are not accessible with aerial vehicles. To truly meet the needs of national leaders and military commanders, this coverage needs to be broad area coverage not enabled by today's space or air-based platforms. However, the spatial resolution of this coverage must still meet or exceed the capability provided by current assets.

### **Options to Meet Future Requirements**

To meet the requirements of national leaders and military commanders in the future both the threat from adversary ASAT capabilities and the need for persistent coverage need to be addressed. This section presents three potential solutions for meeting these two driving requirements: operationally responsive space (ORS) capabilities, networked sensors operating at either LEO or GEO, and a GEO-based sensor.

#### **Operationally Responsive Space Systems**

Operationally responsive space systems are envisioned as a way to rapidly field capability necessary for military commanders.<sup>40</sup> Their utility has increased in importance after the Chinese ASAT test in January 2007. They are seen not just as a means to field new capabilities but also to replace capabilities lost due to adversary action. The ORS concept seeks

to develop small, standardized core satellites outfitted with adapters to which various payloads can interface. These satellites are to be combined with equally responsive launch systems, ground control assets, and tasking systems to provide flexibility not present in current systems.<sup>41</sup>

In the case of optical surveillance, ORS assets would not necessarily be a complete replacement of the lost capability but rather a stopgap measure that ensures partial capability until a fully capable system is available. Herein lies the downside of depending on ORS to meet these new requirements. While ORS provides a capability to compensate somewhat for a satellite lost to an adversary attack, if the replacement satellite is not as capable as the incapacitated satellite, as can be expected, it will have even more limitations on the amount of persistence it can provide.

### **Fractionated Space Systems**

Fractionated or networked space systems offer a novel concept for replacing the large, monolithic systems currently fielded. Such systems divide the functions of a large satellite between many small or micro satellites.<sup>42</sup> These smaller spacecraft are networked together to perform the same function as a large spacecraft. For example, a networked system could have separate spacecraft for each subsystem such as power, payload, and navigation or these subsystems could be hosted on more than one spacecraft. Networked space systems are dependent on a number of capabilities in need of or in development. These include proximity operations, wireless communications and networking, distributed computing, and wireless power transfer.<sup>43</sup> Currently, the Defense Advanced Research Projects Agency is executing Project F6 to investigate the feasibility and value of fractionated space systems.

Such a capability offers many advantages including flexibility and robustness. Fractionated systems allow for flexibility in design and operations through distribution of

functionality. Similar to the concepts of ORS, developing common subsystems for use with alternate payloads allows for late insertion of technologies. When developing today's space systems, the technology baseline must be frozen years before launch because of the intertwined design of these systems. One small change to a subsystem often has a ripple effect throughout the satellite that makes changes unpalatable in both their cost and schedule impact. Using a fractionated system, it is possible to make a change to a small portion of the system by replacing a single microsatellite without impacting the rest of the system. This could even be accomplished after the system is already operational on orbit.

The ability to replace assets on orbit also adds to such a system's robustness. This robustness includes less risk to launch failure and ASATs than a monolithic system. Because such a system could be launched in pieces rather than all at once, a single launch failure would not destroy the whole system. Only those portions of the system destroyed would need to be replaced. The same is true for ASAT attacks and on-orbit failures. Only the nonfunctional portions of the system would require replacement.

Fractionated space systems offer a novel concept to potentially reduce the impact of future space weapons. However, the necessary capabilities mentioned above will require significant progress to be able to replace the most basic spacecraft in the 2030 timeframe. Replicating the complicated optics of a reconnaissance satellite will require another leap to make replacing even today's capabilities a reality. Addressing the requirement for a persistent capability would require an even larger advancement that is unlikely to produce an operational system by 2030.

### **Geosynchronous Orbit Based Sensor**

A geosynchronous orbit based optical system would in many ways be very similar to today's imaging sensors. However, because of the increased distance from the earth, the optics would have to be much larger in order to maintain resolution on par with today's systems.

Basing a system in GEO gives some significant advantages. First, a spacecraft in GEO orbits the earth at the same rate as the earth rotates on its axis. This allows such a satellite to remain over the same point on the Earth with minimal station keeping efforts. In addition to this persistence, a GEO orbit expands the field of view of a spacecraft. Because a satellite in GEO is at an altitude of approximately 35,786 km it is able to look at a much larger section of the earth at one time than a satellite in LEO with an altitude of less than 900 km.

Another benefit of basing an imager in GEO is that it would be less vulnerable to direct assent ASATs and ground-based lasers. As mentioned in the section on space threats, there are only a few demonstrated direct assent ASATs and these systems have only been proven effective against targets in LEO. In addition, current ground-based lasers have only been able to temporarily blind systems in LEO. Basing a system in GEO removes the threat from these current systems but it does not guarantee the safety of future systems. Advances in both lasers and direct assent ASAT launch vehicles could negate the advantage of GEO-basing. While intelligence gathering can detect the advances made in direct assent ASATs and lasers, co-orbital ASATs pose a threat that is even more difficult to counter. These threats can lay in wait for years before striking. This can include orbital transfers from LEO to GEO and everywhere in between. Current space surveillance capabilities allow very small objects to be catalogued and monitored. It cannot however, determine the intent of such systems.

Space threats are not the only hurdle that a GEO-based system must overcome. There are many technical advances that must be made to make such a system a reality. These include

development of large, staring focal planes that will allow a GEO-based system to image theater-sized areas while maintaining today's commercially available resolution of 0.5 m as well as reflectors capable of viewing these same areas. Current systems use monolithic reflectors whose sizes are limited by the payload fairing envelopes of existing launch vehicles. Because of the larger reflectors required by the increased distance from earth, a GEO-based system will require use of an alternate reflector technology such as a deployable reflector. Combining the large reflector and large focal plane with the increased footprint will result in an enormous increase in the amount of data to be handled. This increase will require data handling and exploitation advances in order to allow proper analysis of the collected information.

One major weakness of a GEO-based system is that its location above the equator limits the coverage of the northern and southern latitudes due to the earth's spherical shape. This limitation is seen today in communications and missile warning satellites. Current reconnaissance systems' polar orbits allow them to have world-wide coverage. Because there are many areas of interest in the upper latitudes, a GEO-based system would need to be complemented by other systems to ensure worldwide coverage. One such option would be to pair a GEO-based system with a highly elliptical orbit (HEO) [see Figure 1] system. A HEO or Molniya orbit is an orbit with a 12 hour period that spends roughly 10 hours above the pole. These orbits were first used by the Soviet Union to allow communications satellites to have coverage over the northern latitudes. The Space Based Infrared System (SBIRS), a missile warning system, uses a similar concept. While still in development, it envisions worldwide coverage by employing four GEO spacecraft supplemented by two HEO payloads providing coverage of the northern latitudes.<sup>44</sup> A similar architecture could be used to provide worldwide, persistent, optical coverage. Development of a HEO complement would require additional

sensor development due to the fact that the HEO sensor would be moving relative to the earth unlike the GEO sensor.

None of these three options present a solution which both minimizes the impact of space threat and provides a persistent surveillance capability. Of the three, fractionated systems and ORS present the best chance of recovering after an attack. However, all an adversary needs to counter the advantage gained by these systems is to keep employing its space threat arsenal creating a battle of attrition and infinitely more space debris. While a GEO-based sensor will nominally reduce the threat of current ASAT and laser systems, these systems will improve in time to the point that GEO will likely no longer be a safe haven. However, the GEO-based system does address the issue of persistence in a way that fractionated systems and ORS cannot. A GEO-based system can potentially deliver the ability to continuously monitor a theater-sized area with no concern of over flight restrictions.

### **Investigation of a GEO-based System**

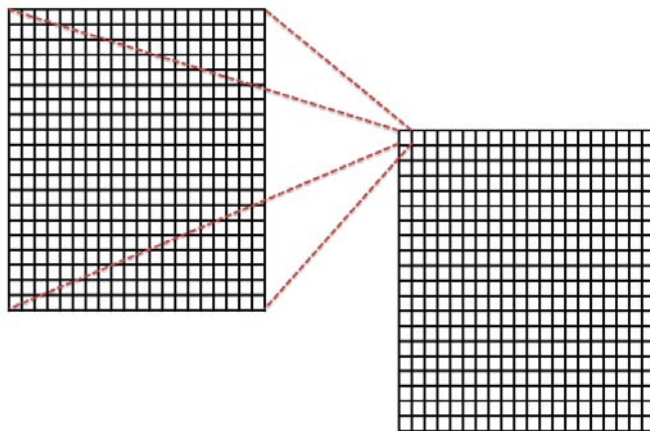
As mentioned above, a GEO-based surveillance system would bring the ability to persistently observe the earth at high spatial resolution over a relatively large area on the earth. This is of course subject to the limitations of any optical sensor which include the inability to see at night or through cloud cover. To field such a system, there are two primary areas of technology development that need to be address. They are advancement in the size of focal planes and progress in deployable reflectors. These will enable a truly revolutionary capability to deliver persistent intelligence to national leaders and military commanders. In order to allow sufficient time for integration and system-level testing, this study uses the year 2020 as the need date for these component technologies to allow for an operational system by 2030.

### **Focal Plane Advances**

The focal plane of an imaging system is where light in the form of photons is sensed and transformed into an analog or digital signal that can be transferred to a ground station for image processing. Stationing an imaging system in GEO will require one of two things to enable image capture due to the lack of relative motion between the sensor and the earth. The first option is to either rapidly slew the spacecraft or include a gimbaled mirror to allow use of a scanning focal plane similar to today's push broom scanners. The other option is to develop staring focal planes. Both focal planes are made of similar materials but the method in which they process incoming photons is very different due to the motion involved. Due to the added design complexity of either rapidly slewing the spacecraft or adding a gimbaled reflector as well as performance superiority, a staring sensor is the preferred option to be explored here.

To capture photons in the visible wavelengths, focal planes can use charge coupled devices (CCD) made of silicon. The key advance needed to enable a GEO-based imager is the growth in size of CCDs. A CCD is essentially a matrix of detectors, often referred to as pixels. The resolution of the sensor is determined by the number of pixels covering the sensor's field of view (FOV). The area detected by an individual pixel is the spatial resolution of that sensor. Therefore, to achieve a spatial resolution of 0.5 m with a field of view of 10 km x 10 km, the sensor would need a CCD of 20,000 pixels by 20,000 (20K x 20K) pixels. Today's visible staring focal planes are limited to 8,000 x 8,000 (8K x 8K) pixels.<sup>45</sup> Doubling this size by 2020 is very likely.<sup>46</sup>

There is very little information in the public domain regarding very large visible focal planes and potential applications. However, there is a significant amount of research ongoing investigating very large focal planes for use in capturing the infrared spectrum. This includes scientific uses such as space telescopes and missile warning. Risk reduction efforts underway



**Figure 6 - Butted Focal Planes**

for the Third Generation Infrared Surveillance (3GIRS) System are looking at the feasibility of developing a focal plane capable of staring at the whole earth to detect ballistic missile launches.<sup>47</sup> As part of this investigation, developers have successfully created an array of focal planes using a technique called butting. This involves laying multiple focal planes together on a surface which results in one large focal plane. Figure 6 shows an illustration of this using a 20 x 20 array of focal planes each with an array of 20 x 20 pixels. Butting focal planes does have the disadvantage that butting causes the loss of use of 10 to 100 rows on the edge of each focal plane.<sup>48</sup> While this is a significant issue for an infrared sensor with a resolution of one kilometer or better, thus losing 10 to 100 kilometers from the field of view, for a visual sensor with a resolution of 0.5 meters, it would only cause the loss of 5 to 50 meters which can be easily compensated for via small changes in the collection aim point ensuring that the same area is not missed in subsequent images.

Pairing expected advances in the size of visual focal planes by 2020 (16K x 16K pixels) and the ability to butt focal planes together, offers a novel method for implementing a true wide area, high resolution imaging capability from GEO. For example, compiling a 100 x 100 array of focal planes each with 16K x 16K pixels would enable 0.5 meter resolution of an 800



kilometer x 800 kilometer area. This would allow an area the size of Afghanistan (647,500 square kilometers) to be constantly monitored.<sup>49</sup> This capability does not come without some challenges. The primary hurdle when assembling large focal planes is maintaining planarity.<sup>50</sup> Current progress on visible focal planes and efforts to butt a small number of focal planes together suggest that it is reasonable to expect the availability of the very large array of focal planes in the 2020 timeframe.

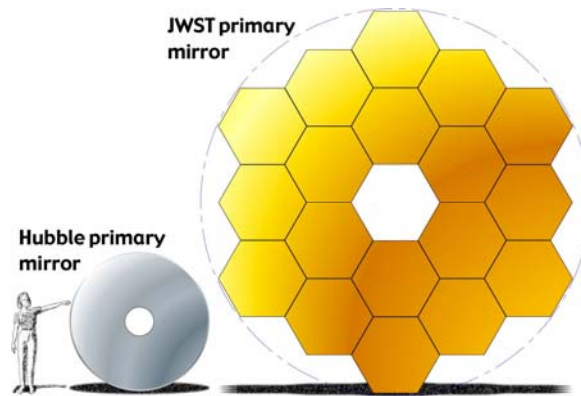
Current efforts on large focal planes in the infrared wavelengths have reached a technology readiness level (TRL) of 6.<sup>51</sup> Technology Readiness Levels are maturity measures of technologies being considered for incorporation into systems.<sup>52</sup> A TRL of 6 is defined as “system or subsystem prototype testing in a relevant environment.”<sup>53</sup> While there is no specified TRL for readiness for incorporation into a system, recent experience points to the need for prototype testing in both a relevant environment such as a thermal vacuum chamber and an operational environment. The success of developers in the 3GIRS risk reduction studies goes a long way toward accomplishing this for very large arrays of large focal planes.<sup>54</sup> To achieve TRL 6 for the scale of array postulated here would require building on the success already demonstrated by assembling and testing a prototype of a large butted focal plane in an environment representative of the space environment. Given the successes seen to date, this should be able to be accomplished by 2020 with relative ease.

### **Deployable Mirror Advances**

The increased distance from the surface of the earth primarily affects the size of reflecting surface required to make a GEO-based imager feasible. Currently the largest acknowledged mirror on orbit is the Hubble Space Telescope with a 2.4 m diameter.<sup>55</sup> The size

of the mirror is limited by the payload fairing size of the largest launch vehicles available, currently the Space Shuttle, the Ariane 5, and the Delta IV Heavy. In order to make a GEO-based optical system a reality, a monolithic mirror cannot be used due to both its dimensions and weight. Research has been conducted to look at the performance of deployable optics. These come in two primary configurations. The first is solid mirrors with foldable structures and the second is the use of gossamer mirrors. Gossamer materials have been suggested as a potential method for dramatically reducing spacecraft weight in order to utilize smaller, cheaper launch vehicles. However, very little research has been conducted in this area which suggests that such materials will be a feasible option by 2030.

On the other hand, folding mirrors have been investigated and are in development for use in space. The James Webb Space Telescope (JWST) is a NASA project to develop an infrared observatory due to be launched in 2013.<sup>56</sup> The JWST is currently in development and utilizes both a folding mirror and folding sun shield because they are too large to fit inside the payload fairing of the JWST's launcher, the Ariane 5. The planned primary mirror for the JWST is 6.5 m in diameter.<sup>57</sup> While the JWST is an infrared imaging system, the mirror technology is applicable to a visible imager as well. The difference between a visual and infrared imager are in the focal plane. Figure 7 shows the difference in size between the JWST primary mirror and the Hubble primary mirror. This shows the magnitude of the size difference as well as the segmentation of the JWST mirror.



**Figure 7 - JWST - Hubble Mirror Comparison**

However, even a mirror the size of the JWST primary mirror would be insufficient to suit the purposes of a GEO-based imager. Such a system will require a mirror of at least 8 m in diameter.<sup>58</sup> For both the JWST and a GEO-based surveillance system, simply folding a large mirror will not be enough to permit use of current launch systems. The total weight of the mirrors will also need to be reduced. Options to accomplish this include use of new, lightweight materials, utilizing thinner mirrors, and the use of a number of smaller mirrors to partially fill the viewing aperture. The JWST uses lightweight beryllium to lower the primary mirror mass to 705 kg compared to the 818 kg glass mirror used on Hubble which is half the size.<sup>59</sup>

Taking a different approach, the Air Force Research Laboratory has investigated the use of mirrors based on a theory of optics developed by Golay.<sup>60</sup> They have developed a concept which uses a number of smaller mirrors to partially fill the viewing aperture. By imaging over a longer period of time, the system is able to capture the image of the entire aperture. Figure 8 shows AFRL's test bed concept using a Golay-3 configuration.<sup>61</sup> Using such a concept allows maximized aperture while decreasing the overall weight of the system. However, use of multiple mirrors, thinner mirrors, and new materials drives precision control requirements not necessary for a monolithic mirror. To replicate a single mirror, the multiple mirrors first must be positioned relative to each other with great precision. When using a single mirror, the surface

must be shaped to tolerances that are fractions of the wavelength to be collected, on the order of ten nanometers for visual collection.<sup>62</sup> For a Golay-type system the various mirrors would have



**Figure 8 - AFRL Golay-3 Deployable Optics**

to be placed within this tolerance relative to each other. Achieving this precision is impossible using either existing or projected deployment devices.

In addition, the thinner mirror materials will not be able to maintain their shape to the tolerances required over the life of their mission. Together, these two challenges will require development of control systems which use actuators to constantly reshape and reposition the mirrors in order to maintain the desired configuration. AFRL built a testbed called the Deployable Optical Telescope to “demonstrate the feasibility and capability of emerging technologies in an integrated space-traceable testbed.”<sup>63</sup> Testing focused on precision deployment and active control of a deployable mirror system under expected vibration conditions. Each of the three mirrors in the AFRL testbed was 0.6 m in diameter resulting in an effective primary mirror diameter of 1.7 m with 29 percent of the aperture filled.<sup>64</sup> Although testing was done in a 1-g environment, it showed that deploying, calibrating, and operating a deployable mirror system is definitely feasible. The ground-based testbed originally was

conceived as a predecessor to a space experiment using a similarly sized test article. This testing would answer remaining questions regarding the ability to control the mirror surfaces in the space environment. Due to competing priorities funding for this testing has not been made available and the program is in a dormant stage.

The next step after a space testbed would be an operational system. The size of such a system is determined using equation a) where  $D$  is the diameter of the primary mirror,  $h$  is the

$$a) \quad D = 1.22 \cdot h \cdot \lambda / R$$

distance from Earth (36,000 km),  $\lambda$  is the wavelength to be observed (0.5  $\mu\text{m}$ ), and  $R$  represents the spatial resolution requirement (0.5 m). This equation results in a primary mirror diameter of almost 42 m for the proposed system. Such a primary mirror would be nearly seven times the size of the JWST primary mirror. A mirror of this size drives a number of issues that would have to be addressed in order for such a system to be operationally feasible. First, the system must fit into existing launch vehicles. The deployability of the optics addresses the volume constraints of existing payload fairings. This is demonstrated by the DOT testbed. While the primary mirror of the DOT is a Hubble-class mirror, when folded, it is one-tenth the size of the actual Hubble Telescope.<sup>65</sup> Using a rough extrapolation, the proposed system could be folded to a volume equal to that of the Hubble Telescope. The second constraint for using existing launch vehicles is the allowable weight. Any system using such a large mirror will have to use innovative methods to reduce the weight of the mirror, its supporting structures, and the control mechanisms ensuring planarity. As mentioned above, JWST has made great strides in this area that will need to be carried forward for the proposed system.

The relative immaturity of the deployable optics in comparison to focal plane technology make development of these optics the driver for when the proposed system would be available.

Whereas the necessary focal plane technology could reach a TRL of 6 relatively easily, deployable optics are currently at a TRL of 4, defined as “validation of component or prototype in a laboratory environment.”<sup>66</sup> The prototype tested, DOT, is also much smaller than the proposed system, therefore to get a larger system to TRL 4, it is necessary to undertake testing with a larger prototype to ensure that the control methods are scalable to the larger system. To attain TRL 6 by 2020, a significant amount of investment is required on the part of the U.S. Government. Such investment would make it probable that a large deployable optic system would be available for full system integration by 2020. However, given the DOT program’s dormancy and shrinking defense budgets, it is not likely that this investment will be made.

In addition to the technology development for large deployable optics, another barrier to an operational system exists. This is the ability to test the system on the ground prior to launch. Currently, such systems undergo extensive ground testing to ensure all subsystems are functioning properly prior to transit to the launch base. For the proposed optical system, component testing of the focal planes and the deployable optics would precede subsystem testing with the focal planes and optics integrated which would lead to full system testing after the optics are integrated with the rest of the spacecraft components. Each level of testing would require both functional and performance testing in a space-like environment. The sheer size of both the butted focal planes and the deployable optics will necessitate facilities that are beyond any current capacity. This will also require a large investment on the part of the government that is unlikely in the near term.

### **Conclusions and Recommendations**

A GEO-based reconnaissance system presents a unique solution to the problem of persistent surveillance. While it will require significant technical progress in focal plane size and

deployable optics, a great deal of research has been conducted that shows that deploying an operational system by 2030 is very feasible, although unlikely due to funding constraints. Such a system will provide national leaders and military commanders unprecedented coverage of areas where access to air space is denied. A GEO-based imager can provide theater-wide coverage with the spatial resolution of today's best commercial systems. This will be a revolutionary capability that will change the way intelligence serves the commander.

To provide comprehensive coverage, a GEO-based optical system will require augmentation. Two methods can accomplish this without major additional technological developments. The first is to add an infrared focal plane to supplement the proposed optical focal plane. This addresses an optical system's limitation of requiring light. An infrared system will allow the satellite to image during night in addition to the visual system's daytime capability. Images from an infrared subsystem of the same scale as the optical subsystem will not be able to match the optical system's resolution due to the difference in wavelength (0.5  $\mu\text{m}$  for visual,  $\sim 5\mu\text{m}$  for infrared) but will be able to present very useful information for decision makers and warfighters by observing the heat signature of objects on the ground. In addition to adding an infrared focal plane, a comprehensive system should include assets in HEO orbits as well. The spacecraft in HEO would compensate for the GEO limitation in observing the earth's poles, specifically the northern latitudes which are of greater strategic importance. Spacecraft in HEO can utilize the same technology as the GEO spacecraft with modifications to account for the motion of the system with respect to the earth.

However, even a comprehensive system answers only one of the two requirements identified in this paper. The issue of adversary threats to space systems is not totally addressed. While moving from LEO to GEO reduces the threat of direct ascent ASATs and ground-based

laser systems, co-orbital ASATs represent a large threat due to a lack of comprehensive space situational awareness. Due to the limitations of current space surveillance systems, it is more difficult to identify objects in GEO than in LEO. Systems such as the Space Based Space Surveillance System will help to mitigate but not totally alleviate this problem. While it will be possible to better identify objects it will still be supremely difficult to determine the intent of other spacecraft. For example, a co-orbital ASAT would look a lot like a maintenance spacecraft or a scientific satellite.

Even if identification of spacecraft and intent were able to be accomplished, there is still the problem of what to do about it. To enable the free operation of systems such as a GEO-based imager, protection measures must be developed. These can be part of the overall system or separate systems whose job it is to patrol various orbits and protect a nation's spacecraft from adversary threats. Without such protective measures, adversaries can hold systems that represent large investments by their countries in jeopardy.

A GEO-based surveillance system is a worthwhile investment that will provide a breakthrough capability to national decision makers and warfighters. To make such a system a reality, the U.S. must focus research on expanding the size of visual focal planes and development of full-scale deployable optics. Combining the fruits of these two efforts will provide a persistent surveillance capability that meets user requirements. Prior to operation of this system, the U.S. must develop a comprehensive space object tracking architecture as well as protection systems to ensure the unimpeded operation of our most crucial space systems.



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## APPENDIX A

### ACRONYMS

3GIRS – Third Generation Infrared Surveillance  
ABL – Airborne Laser  
AFRL – Air Force Research Laboratory  
ASAT – Anti-satellite  
CCD – Charge Coupled Device  
CENTCOM – Central Command  
DARPA – Defense Advanced Research Projects Agency  
DEW – Directed Energy Weapon  
DoD – Department of Defense  
DSP – Defense Support Program  
EMP – Electromagnetic Pulse  
FOV – Field of View  
GEO – Geostationary Orbit  
GOES – Geostationary Operational Environmental Satellite  
GSD – Ground Sample Distance  
HEO – Highly Elliptical Orbit  
HPM – High Power Microwave  
ISR – Intelligence, Surveillance, and Reconnaissance  
JWST – James Webb Space Telescope  
LEO – Low Earth Orbit  
MIRACL – Midwave Infrared Chemical Laser  
NASA – National Aeronautics and Space Administration  
NGA – National Geospatial-Intelligence Agency  
NOAA – National Oceanographic and Atmospheric Administration  
NRO – National Reconnaissance Office  
ORS – Operationally Responsive Space  
SM-3 – Standard Missile-3  
TRL – Technology Readiness Level  
UAV – Unmanned Aerial Vehicle  
USAF – United States Air Force

## APPENDIX B

### DEFINITIONS

Apogee – The point on an orbit that has the highest altitude.

Geostationary Orbit – A circular orbit with an orbital period equal to time it takes the Earth to rotate 360 degrees and an inclination of 0 degrees. Such an orbit allows a spacecraft to remain over the same point on the Earth's equator.

Geosynchronous Orbit – An orbit with an orbital period equal to time it takes the Earth to rotate 360 degrees. Such an orbit allows a spacecraft to remain over the same area of the Earth. The size of this area is determined by the inclination of the orbit

Ground Sample Distance – The distance at which a sensor spatially samples the target scene.<sup>67</sup> This measure corresponds to the size of the area a single pixel is imaging in the proposed concept.

Highly Elliptical Orbit – Also referred to as Molniya orbits, these orbits have ~12 hour orbital periods and have an inclination of either 63.4 degrees or 116.6 degrees. These inclinations cause the rate of change of perigee to be zero. Typically the perigee of these orbits is placed in the southern hemisphere to allow a spacecraft to spend nearly 11 hours of each orbit near apogee in the northern hemisphere giving excellent coverage of northern latitudes.<sup>68</sup>

Low Earth Orbit – An orbit with an altitude less than 1,000 km.<sup>69</sup>

Orbital Period – The time it takes a spacecraft to complete one orbit of the Earth. Examples include roughly 90 minutes for a low earth orbit and 24 hours for a geosynchronous orbit.

Perigee – The point on an orbit that has the lowest altitude.

Polar Orbit – An orbit with an inclination of 90 degrees allowing a spacecraft to fly directly over the poles.

Push broom Scanner – A focal plane used in remote sensing which uses linearly arranged detector elements that capture one line across the swath at each integration time. The term push broom comes from the read-out process, which delivers one line after another, like a push broom across the ground track.<sup>70</sup>

Sun-synchronous Orbit – A near-polar orbit in which the orbital plane remains approximately fixed with respect to the sun.<sup>71</sup> Such orbits are especially useful in imaging applications as the spacecraft will pass over the same target at nearly the same time during a subsequent orbit allowing the lighting to the scene to be consistent for use in comparison.

Staring Sensor – Also referred to as a matrix sensor, a focal plane which uses a matrix of detectors to capture a complete image each integration time.<sup>72</sup>

## Appendix Notes

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<sup>67</sup> Larson and Wertz, eds. *Space Mission Analysis and Design*, 276.

<sup>68</sup> Ibid, 143-144.

<sup>69</sup> Ibid, 181.

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